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INTRAFORMATIONAL CORRUGATED ROCKS

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INTRODUCTION

It is the purpose of this paper to enter into a general discussion of intraformational contorted rocks, with emphasis upon the modes of origin of the different types. During the last eighty years various examples have been described, but it is surprising how few are the cases which have been discussed in sufficient detail to furnish the data necessary for their classification on the basis of origin. Evidently these interesting and often puzzling structures have not received the attention which they deserve. In the present attempt to make a tentative genetic classification of intraformational corrugations, examples, mainly from American localities, are given to illustrate the various types. Because of the lack of certain critical data, it is difficult or impossible to be very sure of the proper classification of some of the cases.

DIFFERENTIAL MOVEMENT ACCOMPANYING THRUST FAULTING

Excellent examples of corrugated strata between practically undisturbed strata occur in the walls of the postglacial gorge at

Trenton Falls, New York, where the contorted beds lie at two distinct horizons within the Trenton limestone formation, there about 300 feet thick. The lower contorted zone, 4 to 6 feet thick, is visible only near the crest of the lower part of High Fall and in the upper end of the gorge near Prospect Village where the strata are highly inclined against a thrust fault surface. The upper contorted zone, 5 to 15 feet thick, is well exhibited along the path opposite High Fall (Fig. 1, upper part) from which place it is clearly traceable in the walls of the gorge for nearly 2 miles northward to Prospect (Fig. 1, lower part).

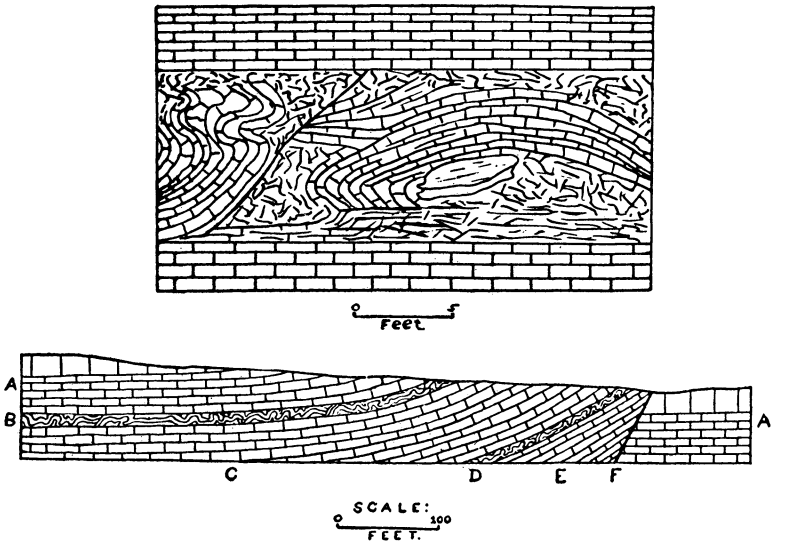


FIG. 1.—Upper figure: sketch of part of the upper contorted zone at Trenton Falls, New York. Lower figure: north-south structure section showing the positions of the contorted zones within the Trenton formation and their relation to the thrust fault at Trenton Falls, New York.

In both the undisturbed and the corrugated portions of the formation the impure limestone layers average only a few inches in thickness, and they are separated by thin partings of shale. Within the contorted zones the strata are in some cases scarcely disturbed; in some cases they are only gently folded or tilted; but most commonly by far they are highly folded, contorted, and even fractured.

The explanation offered by the writer is that the contorted zones were produced by differential movements within the mass of the Trenton limestone. The displacement (140 feet) of the thrust fault at Prospect Village was sufficient to cause the beds of the middle Trenton to be shoved over the upper Trenton. Figure 1 (lower part) shows the relation of the contorted zones to this fault. It is easy to see how, when the force of compression was brought to bear in this region, the higher Trenton beds on the upthrow side must have moved more easily and consequently faster than the lower Trenton beds. For instance, the portion *A* in Figure 1 (lower part) being separated from *C* by an intermediate mass *B* of possibly slightly less rigidity moved over *C* and caused the portion *B* to become ruffled or folded and fractured because this portion took up most of the differential movement. The portion *B* needed to be only slightly less rigid than the adjacent strata and this slightly reduced competency is due to somewhat thinner limestone layers separated by relatively thicker shale partings. A similar explanation applies to the lower contorted zone. According to this explanation the corrugated zones indicate horizons along which the differential movements took place, and no great amounts of differential movement were necessary to produce the contortions.

Grabau[1] states that

> These disturbances at Trenton Falls have been variously explained, the general conclusions of geologists being either: (1) that they were truly tectonic —lateral pressure having resulted in the folding of certain strata while others took up the thrust without deformation, or (2) that they were due to squeezing out of certain layers under the weight of overlying rock masses. Both explanations are unsupported by the detailed characteristics of the folds and their relationship to the enclosing layers.

The writer agrees that these two explanations must be ruled out, but he does not agree with Grabau who accepts Hahn's[2] subaqueous slumping or gliding hypothesis, described later in this paper, without even mentioning the tectonic differential slipping hypothesis (above outlined) which was first applied by the writer[3] to the Trenton

[1] A. W. Grabau, *Principles of Stratigraphy* (1913), p. 784.

[2] F. Hahn, *Neues Jahrb. Beil.*, Vol. XXXVI (1913), pp. 1–40.

[3] W. J. Miller, *Jour. Geol.*, Vol. XVI (1908), pp. 428–33.

Falls contorted zones in 1908, and further elaborated in 1915.[1] Arguments against Hahn's hypothesis are there entered into somewhat in detail. In the opinion of the writer, differential movement (not always as an accompaniment of thrust faulting) is involved in many, if not most, cases, of intraformational corrugations.

Intraformational contorted beds of essentially the same origin as those at Trenton Falls, only on a larger scale, occur within the straight-bedded limestones of Turtle Mountain, Frank, Alberta,

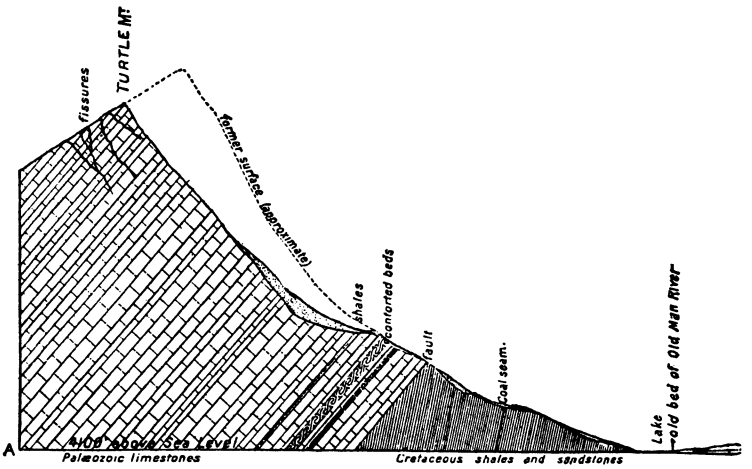


FIG. 2.—Section showing the position of the contorted limestones and the relation of the contorted beds to the great thrust fault at Frank, Alberta, Canada. (After R. W. Brock.)

Canada. Accompanying Figure 2 after Brock[2] shows the position of two corrugated zones of more shaly material intercalated between straight beds of limestone and parallel to a great thrust fault on its upthrow side. The writer would explain these corrugations as due to differential slippings within the limestone with resultant crumpling of the more shaly layers during the process of thrust faulting of the Paleozoic limestone over the Cretaceous strata.

Many years ago Logan,[3] in his description of a section 1,210 feet in thickness of Devonian strata on the Forillon peninsula of

[1] W. J. Miller, *N.Y. State Mus. Bull. 177* (1915), pp. 135–43.

[2] R. W. Brock, *Dept. Interior Canada, Ann. Rept.*, Part 8.

[3] W. Logan, *Geol. Can.* (1863), p. 391.

Gaspé in the Gulf of St. Lawrence, called attention to a remarkable example of intraformational corrugations. Logan says:

It would appear as if the layers, after their deposit, had been contorted by lateral pressure, the underlying stratum remaining undisturbed, and had then been worn smooth before the deposition of the next bed. Where the inverted arches of the flexures occur, some of the lower layers are occasionally wanting as if the corrugated bed had been worn on the under as well as the upper side. The corrugations are precisely in the direction of the dip, and the peculiarity is not confined to a small part of the deposit.

He states that the same structure occurs at localities a mile apart.

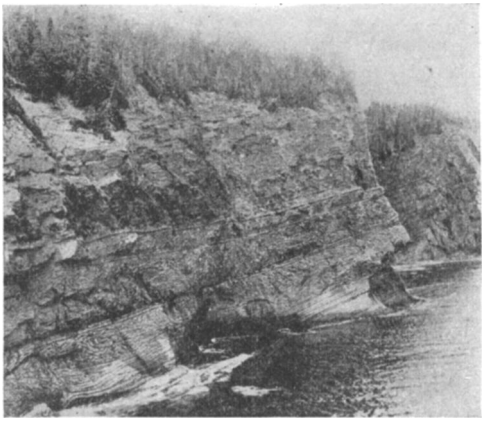


FIG. 3.—Contorted strata within Devonian limestone at Cape Gaspé, Quebec. (After J. M. Clarke.)

John M. Clarke, who has observed the Gaspé occurrence, and who has kindly permitted the use of the accompanying picture (Fig. 3), says:

Crinkled strata lying between strata which show no evidence of dislocation are not of infrequent observation but, in most of the recorded instances, the crinkled layer is of softer stuff (that is, a highly aluminous mud rock) than the rigid beds above and below. The brilliant exhibition of this phenomenon on the cliffs of Cape Gaspé, first sketched by Sir William Logan, is not of this character. Here the middle deformed beds are of thin limestone leaves like those which bound them. They are crumpled into sharp, much involved and overlapping curves in which the limestone plates are broken sharply across. It seems very doubtful if any other explanation can be brought forward for

this exceptional occurrence than that generally adopted for those of the first named category; a sliding of soft sea bottom deposits on a sloping surface under gravity, helped forward perhaps, if on a large scale, by earthquake shock or some other jolt-like impulse. . . . . It follows from the conception of these structures that the deformation was contemporaneous, and preceded the deposition of the overlying beds.[1]

For the reasons below listed the writer is strongly inclined to the conclusion that the corrugated zone at Gaspé developed as a result of differential movement within a great block of strata while it was being thrust faulted. (1) If we accept the hypothesis of subaqueous sliding, it is necessary to attribute the nearly straight upper surface truncating the contorted zone to erosion, but the very character and uniformity of both the contorted and inclosing strata seem to render this extremely improbable; (2) the worn character of both the upper and lower surfaces of the contorted zone, with certain beds locally missing as noted by Logan, are best explained on the basis of differential movement within the mass of limestone; (3) that the conditions were very favorable for differential movement is borne out by the fact that the contorted zone lies not far from the bottom of a large block of Devonian strata which has been extensively thrust faulted over Cambro-Ordovician strata; (4) the strike of the contorted zone is approximately parallel to the strike of the thrust fault; (5) the corrugations conform to the direction of dip of the inclosing beds; (6) according to Logan's section, the corrugations developed just where the conditions were most favorable for differential movement, that is, in the weakest (most shaly) part of a mass of the strata 200 feet thick with appreciably more arenaceous and resistant strata above and below this mass; and (7) the rather puzzling occurrence of the two nearly straight, thin beds within the contorted zone (see Fig. 3) may be more reasonably explained on the basis of differential movement than on the basis of subaqueous gliding because, as revealed by careful examination of the figure, these layers, as well as the layers capping the contorted zone, show clear evidence of having been deformed and even cut across locally by the corrugations, thus indicating that the contortions took place after deposition of those layers.

[1] Personal communication from Dr. Clarke.

DIFFERENTIAL MOVEMENT ACCOMPANYING NORMAL FAULTING

Up-drag of strata commonly takes place as a result of friction during movement on the downthrow sides of normal faults. Under proper conditions drag folds of the nature of intraformational corrugations develop as a result of differential movement of the bending strata. A good example has been observed by the writer in the bed of the Connecticut River just below the dam at Holyoke. A normal fault is clearly traceable in the bed rock across the river a few rods below the dam. From the fault south for 150 yards the strata (sandstone and shale) show dips of 25 to 40 degrees to the south due to up-drag, and they strike parallel to the fault. About 150 yards south of the fault there is a notably disturbed zone of thin-bedded dark shale with strike parallel to that of the fault. It shows clearly along the strike for 200 yards. The disturbed zone, varying in thickness between 4 and 10 feet, is overlain by fairly well-bedded red sandstone, and underlain by thin-bedded dark shale much like that of the disturbed zone. Next below there is sandstone. The folded zone does not terminate abruptly at either summit or base, but the top is much the more regular, coming close to the overlying sandstone. Even the sandstone, for a foot or so above the shale contact, is locally somewhat bent. The whole body of the rock in the bed of the river south of the fault plainly shows the effects of differential movements which took place during the process of normal faulting. One belt of weak, thin-bedded shale overlain by relatively rigid sandstone became moderately corrugated, the corrugations being of the nature of drag folds produced by differential movements. That the corrugations must have developed after the deposition of the overlying sandstone layers is proved by the fact that the lower part of the sandstone is in many cases moderately bent just like the immediately underlying shale. It seems impossible to escape the conclusion that this corrugated zone is of tectonic origin, that is, the result of differential movement accompanying normal faulting.

DIFFERENTIAL MOVEMENT ACCOMPANYING REGIONAL FOLDING

The principle of differential movement of strata is well illustrated in many regions of notably folded rocks. Differential move-

ments take place between the relatively more competent beds with not uncommon development of corrugations of the nature of drag folds between them. According to Leith: "The stronger beds tend to assume the 'parallel' type of folds in which the principal adjustment is between the beds rather than within them. This readjustment or slipping is concentrated in the intervening weaker layers. The folds of the weaker layers are really 'drag folds' due to differential movement between the controlling harder layers."[1]

Excellent examples of intraformational corrugated strata believed to have resulted from differential movement accompanying regional folding were observed by the writer some years ago at Baldhead Cliff near Ogunquit, Maine. The perfectly stratified thin-bedded rocks are there interbedded quartzite and phyllite. That the region has been subjected to severe lateral compression is evidenced by the fact that the strata stand in nearly vertical position. Figure 4 is a ground plan sketch showing the detailed structure of one of these corrugated zones about 9 feet thick, although the quartzite layers are really less conspicuous than indicated in the diagram. The corrugated zone, consisting very largely of phyllite, is not sharply delimited from the adjacent straight layers of predominant quartzite on either side. In most cases slight faulting has taken place along the axes of the sharp folds, but, as a rule, individual sharp folds or faults rarely extend all the way across the contorted zone. The folds are uniformly overturned toward the east. Fracture cleavage is well exhibited in the phyllite layers a few inches thick which lie within the quartzite on either side of the contorted zone. The cleavage cracks are uniformly inclined toward the east, as are the folds. "When a slate or shale is folded between two competent layers, such as quartzite, the cleavage produced in the slate affords clear evidence of slipping or shearing between the quartzite beds."[2]

All the evidence points to the tectonic genesis of the above-described intraformational corrugated strata. The corrugations must have developed after all the strata were deposited because the folded zone grades into the non-folded strata on either side.

[1] C. K. Leith, *Structural Geology* (1913), p. 114.

[2] *Ibid.*, p. 119.

Under conditions of differential movement the wide belt of predominant phyllite yielded by development of corrugations, while the thin bands of phyllite between much quartzite on either side yielded by development of fracture cleavage.

In the Marquette synclinorium of Michigan intraformational corrugations are shown on large scales in the slate formations which lie between quartzite formations.

During the summer of 1921 the writer was impressed by the fine exhibitions of intraformational contorted strata of Proterozoic

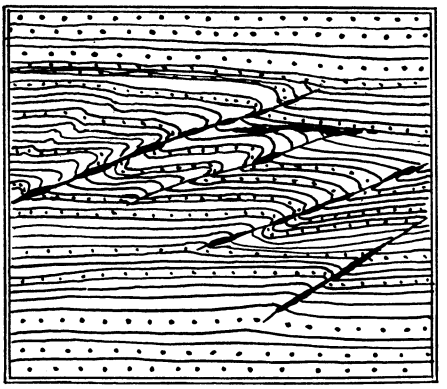


FIG. 4.—Ground-plan sketch of intraformational corrugated phyllite and quartzite near Ogunquit, Maine. The black lenses are quartz. Contorted zone about 9 feet wide.

age on both small and large scales in Glacier National Park. In the wall of the great Swiftcurrent cirque, only a few rods from the trail, the strata are notably folded and even crumpled through a thickness of 30 to 40 feet, and for a distance of a few hundred feet, while on all sides the strata are undisturbed except for the moderate regional tilting. The folding rocks are not sharply separated from the others. On the grand scale the strata are very irregularly contorted through a thickness of hundreds of feet in the face of the mountain between Gunsight Lake and Gunsight Pass with non-contorted strata above, and also at the same general horizon on either side. These contorted beds have quite certainly resulted from local differential movements within the great body of Proterozoic strata either during the development of the synclinal structure

of the park, or during the tremendous process of thrust faulting of the district, or both.

In a discussion of the highly folded gold-bearing series of Nova Scotia, Faribault[1] has figured and described some interesting cases of intraformational corrugated quartz veins in slate lying between beds of quartzite. He says: "Interstratified (quartz) veins often exhibit a remarkable folded or corrugated structure within the beds of slate that contain them. The corrugations, or crenulations, usually occur at or near the apex of the anticline, and run parallel with one another and in a direction approximately parallel with the axis of the fold." He believes (1) that the veins were formed during the folding of the region; (2) that, due to differential motion within the relatively weak or plastic slate containing veins which were formed early in the folding process, the veins and inclosing slate were corrugated; and (3) that such motion resulting in corrugations took place mainly at the apexes of the folds.

DIFFERENTIAL SQUEEZING ACCOMPANYING REGIONAL FOLDING

Lateral pressure may result in the folding of certain weaker strata while adjacent more resistant strata take up the thrust either without so much folding or by being fractured instead of folded. Intercalated beds of limestones are especially likely to yield in this manner. Interesting effects of differential squeezing in the folded Algonkian strata of the Marquette district of Michigan have been described by Van Hise, Bayley, and Smyth[2] who say:

> Along the contacts of the (Kona) dolomite beds and the quartz(ite) layers accommodation was necessary, and in places a bed of limestone may be seen bent into a series of anticlines and synclines, the overlying quartzite not being similarly bent, but being compressed and brecciated, thus making a pseudo-conglomerate. . . . . When the series was folded the more plastic limestone yielded to the pressure, in both a major and a minor way, by folding, while the brittle quartzite was fractured through and through, the movement of the fragments over one another, and of the beds as a whole, being sufficient to truncate the minor waves of the marble.

[1] E. R. Faribault, *Can. Geol. Surv., Guide Book No. 1*, Part 1 (1913), pp. 174–88.

[2] Van Hise, Bayley, and Smyth, *U.S. Geol. Surv., Mon. 28* (1897), pp. 242–43.

Even in this case some shearing action or differential slipping was a factor in the process.

Prouty[1] has described the crumpling of thin beds of marble between thick beds which latter yielded by fracturing and faulting.

The principle of differential squeezing appears to be not uncommon in various regions of folded strata.

DIFFERENTIAL MOVEMENT UNDER THE ACTION OF GRAVITY

Fine examples, believed by the writer to belong in this category of intraformational contorted strata, are to be found in the post-glacial clays of various regions. The following observations made by the writer upon the clays in and near Northampton, Massachusetts, give a fair idea of the nature of the foldings and their origin. In the bank of the Connecticut River 2 miles east of Northampton, 12 to 14 feet of nearly horizontal, thin-bedded, perfectly stratified clays are overlain by 10 to 15 feet of stratified sands. The clay contains two contorted zones—a lower one 1 to 2 feet thick, and an upper one 4 to 8 inches thick—separated by 8 or 9 feet of the ordinary non-contorted clay. These corrugated zones are clearly traceable for several hundred feet. Immediately above each contorted zone, the non-contorted layers are in many places somewhat wavy or slightly folded. Different portions of the same contorted zone show different degrees of folding, the clay beds in some cases being only moderately folded, while in others they are intensely twisted, pulled apart, and even overturned. Some of the straight beds contain notable amounts of very fine sand, but the contorted beds consist of distinctly less sandy clay. The corrugations almost invariably have strikes parallel not only to each other but also to the notable dip (several degrees) of the clay beds in general. The under surface of each contorted zone is usually very straight, while the upper surface is commonly somewhat irregular (Fig. 5).

In the South Street clay pit of Northampton the writer has observed a very fine highly contorted zone of clay sharply intercalated between beds of clay whose stratification surfaces are almost straight. The straight beds consist of alternating, very fine-grained,

[1] W. F. Prouty, *Geol. Surv. Ala., Bull. 18* (1916), p. 170.

sandy clays and pure clays, while sandy clays are distinctly less conspicuous among the contorted beds. Figure 6 represents a detailed sketch of part of this corrugated zone, a feature of exceptional interest being the only slightly disturbed layer of fine-grained, sandy clay lying in the midst of the contortions. This contorted zone about 8 inches in thickness may be traced for a number of rods in the walls of the clay pit, but its full extent is unknown. Above it about a foot there is another corrugated zone lying between prac-

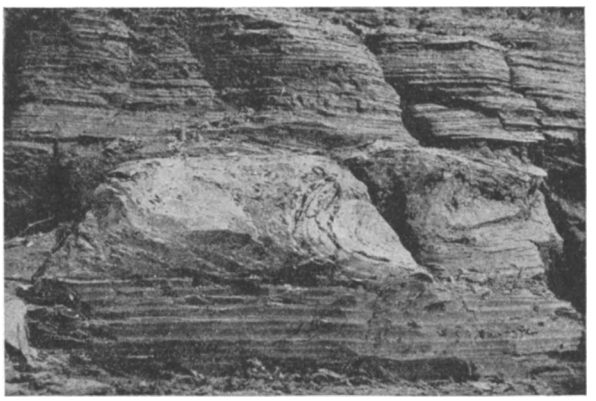


FIG. 5.—Highly contorted zone (8 inches thick) of clay between practically undisturbed beds of clay and sandy clay in the bank of the Connecticut River 2 miles east of Northampton, Massachusetts.

tically undisturbed beds. Within the clay pit the beds show a very appreciable dip of at least several degrees to the southeast.

It seems impossible to explain intraformational contorted clays like those just described except as a result of differential movements after the clays overlying the contortions were deposited. An explanation commonly given for such phenomena, but rarely if ever supported by anything like reasonable proof, is that the contortions were caused either by ice thrust, or the bumping or crowding of icebergs on surface layers which were afterward covered by more clays. Some facts opposed to such a hypothesis are: (1) the remarkably uniform thinness of the corrugated zones of such wide extent which could hardly have resulted from ice action upon surface layers, the development of such zones under considerable

weight of overlying materials being far more plausible; (2) there are no notable irregularities or depressions at the tops of the corrugated zones such as must have developed in the case of crumpling of surface layers with these depressions first filled by the succeeding deposits; (3) the moderate disturbance of the beds immediately overlying the corrugated zones, while those just underneath are distinctly straighter, strongly point to differential movements after the overlying beds were laid down; and (4) the only slightly disturbed thin bed of fine sandy clay in the midst of the contorted South Street clays, as well as the relatively straight beds of similar material just above and below the contortions, are best accounted

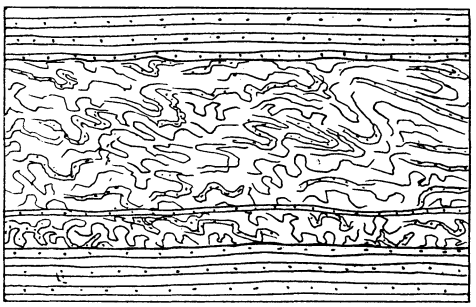


FIG. 6.—Contorted zone in South Street clay pit of Northampton, Massachusetts

for on the basis of differential movements, the thin, clay-rich, very plastic beds having yielded by crumpling, while the much less plastic sand-rich beds did not crumple. It is out of the question to look upon the upper surfaces of the corrugated zones as erosion surfaces because these perfectly stratified, thin-bedded, postglacial clays everywhere plainly show that they were deposited without a break in very quiet water.

The hypothesis of differential movement does not necessarily preclude the possibility of subaqueous slumping for it is plausible to think of differential movements within masses of the clays which may have shifted more or less down the gently sloping delta fronts in the postglacial lake of the Connecticut Valley. The action of gravity alone, or of gravity aided by an occasional earthquake, may have caused the movements. It is more likely, however, that

the movements mostly took place much later, that is, since the river has cut deeply into the distinctly dipping clay deposits so that, under the action of gravity or gravity aided by earthquake shocks, overlying beds have moved differentially over lower-level beds in the general direction of the dip. In some local cases differential movements within clays may possibly have been caused by the crowding action of ice against upper portions of clay deposits as explained later under another caption.

A few examples of apparently similar intraformational clays from other regions will be cited, with various explanations which have been offered to account for them. In regard to corrugations in clays near Boonville, New York, Vanuxem[1] eighty years ago said: "These interesting forms of disturbance were no doubt the result of unequal, local, and lateral pressure." A very similar excellent example of intraformational sand and clay in the Devil's Lake region of Wisconsin is figured and described by Salisbury and Atwood,[2] who say: "The grounding of an iceberg on the surface before the overlying layers were deposited, or the action of lake ice, may have been responsible for the singular phenomenon."

M. E. Wilson has described and figured[3] interesting cases of intraformational contorted and broken clays in Timiskaming County, Quebec, and in regard to their origin he says: "Whatever the cause of these peculiar deformational structures, it is evident that they were contemporaneous with deposition, for the stratification is uniform in both the overlying and underlying beds."

In Albany County, New York, according to Nason,

> A layer of blue clay about a foot in thickness and one hundred feet long is crumpled and gnarled, appearing as though its laminae had been disturbed by some dragging or shoving weight, while above and below the layers are exactly parallel and wholly undisturbed. . . . . Bearing in mind the fact that the clay banks are underlain by sand, the water circulating through these sands gradually undermines the clay bank and tilts it to such an angle that one part of a bed would slide over the other, only leaving visible marks along the particular stratum disturbed, and in the form of crumplings. Many of the clays lie at an angle to the horizon, and only a slight tilt would suffice to give rise to a slip.[4]

[1] L. Vanuxem, *Geol. N.Y.*, Part 3 (1842), p. 215.

[2] Salisbury and Atwood, *Jour. Geol.*, Vol. V (1897), p. 143.

[3] M. E. Wilson, *Can. Geol. Surv., Mem. 103* (1918), p. 142 and Pls. 15–16.

[4] F. L. Nason, *N.Y. State Mus. Rept. 47* (1893), p. 465.

It is to be noted that Nason's explanation clearly involves the principle of differential movement which is advocated by the present writer as the cause of most intraformational contorted clay beds.

SUBAQUEOUS GLIDING OR SLUMPING

The hypothesis of subaqueous gliding has been elaborated by Hahn[1] who has considered most cases of intraformational contorted strata to belong in that category. According to Hahn's hypothesis a lenslike mass breaking loose from any cause (e.g., earthquake shock) would glide down a subaqueous slope and, because of the striking of some obstacle on the bottom and increased friction and water pressure, the gliding mass would come to rest only after it had become considerably deformed or contorted. Sediments would then be deposited in normal order on top of the crumpled layer. The most intense folding would be toward the front of the transposed mass, and of course the strike of the folds would be at right angles to the direction of the moving mass. Conditions for such gliding are regarded as favorable at many places on the marginal sea bottom.

In the paper above cited, Hahn especially refers to the intraformational contorted zones at Trenton Falls, New York, as typical examples of submarine slumping among ancient strata. In a paper already published the writer has given reasons for believing that Hahn's hypothesis cannot possibly account for the Trenton Falls occurrences.[2] Hahn has regarded most cases of intercalated corrugated strata as results of subaqueous gliding, while the present writer regards most of them by far as results of differential movements within the masses of strata.

T. C. Brown[3] has described what appears to be a clear case of intraformational folding in Paleozoic strata near Bellefonte, Pennsylvania. In regard to this occurrence Brown says in part: "At periodic intervals these beds of calcareous mud and intermingled pebbles slumped or slid along the bottom under the influence of gravity. At the time of the slump or slide the matrix around the pebbles consisted of incoherent lime mud or paste. As it moved

[1] F. Hahn, *Neues Jahrb. Beil.*, Vol. XXXVI (1915), pp. 1–41.

[2] W. J. Miller, *N.Y. State Mus. Bull. 177* (1915), pp. 140–43.

[3] T. C. Brown, *Jour. Geol.*, Vol. XXI (1913), pp. 241–43.

it developed unsymmetrical waves or ripples in its mass." After the mass came to rest more lime mud was deposited upon its surface. Since then the whole has been solidified. The contorted zone shows notable variations in thickness from a few inches to several feet (Fig. 7). Certain criteria which seem to rather definitely place this occurrence in the category of subaqueous gliding, and which particularly distinguish it from the above-described examples believed to have resulted from differential movements after deposition of the overlying layers, are the following: (1) the notable variations in thickness of the contorted zone locally, even within a few feet; (2) the very irregular upper surface of the folded zone,

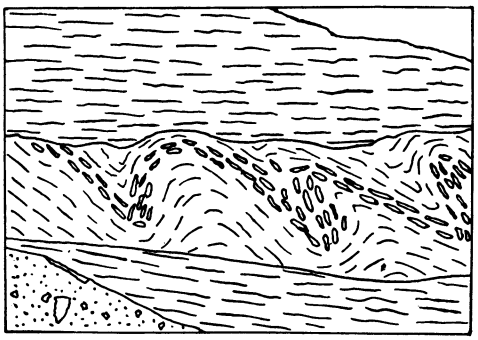


FIG. 7.—Folded limestone and limestone-conglomerate, several feet thick, between non-folded beds near Bellefonte, Pennsylvania. (After T. C. Brown.)

and the rather regular under surface; (3) the bulging of the immediately overlying strata over the little anticlinal folds; and (4) the distinct evidence of the filling of the depressions on the upper surface of the corrugated zone before the general layers of overlying materials were laid down.

D. W. Johnson has kindly allowed me to reproduce a picture (Fig. 8) of a moderately corrugated zone within the cross-bedded Triassic red beds near Kanab, Utah. Regarding the occurrence he says:

> The crumpling and faulting must have taken place during the process of deposition, for the erosion plane beveling the deposit a few inches above the corrugations, and upon which the next layer of cross-bedded sand was deposited, shows no disturbance. I have therefore attributed the corrugations and miniature faults to slumping or settling of the deposit as it was built forward, delta-like, under the influence of current action.[1]

[1] Personal communication from Professor Johnson.

In view of the fact of the very moderate degree of corrugation, a slight amount of subaqueous slumping or forward settling, perhaps under earthquake impetus, would have produced the structures. There may have been no actual gliding over the lower erosion surface at all. Erosion intervals, under the conditions of shifting currents during the deposition of the cross-bedded sandstones, would be expected. The corrugations of the disturbed zone might possibly have resulted from slight differential slipping

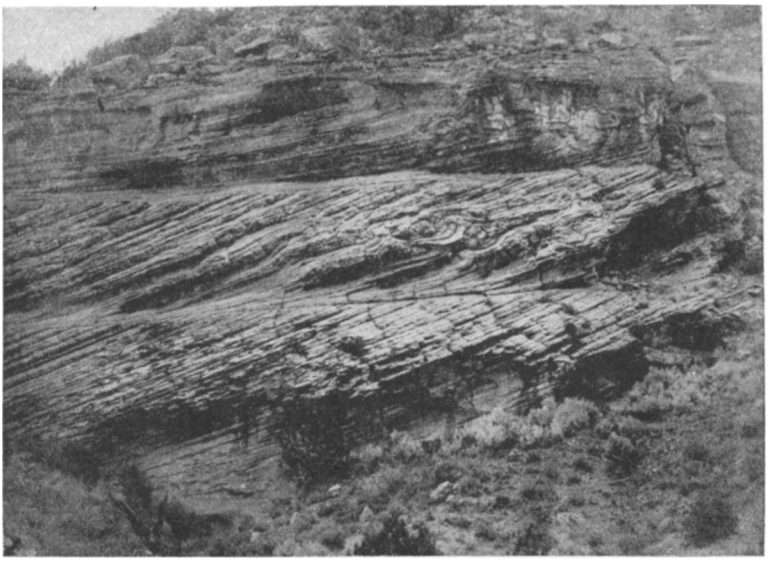


FIG. 8.—Intraformational cross-bedded, corrugated, Triassic sandstone near Kanab, Utah. (After D. W. Johnson.)

along the erosion surfaces but, in spite of certain outward resemblances to the intercalated contorted zones above described as due to differential movement after deposition of the immediatley overlying beds, the writer believes that the structures in the Kanab occurrence are essentially different, and that they are correctly interpreted by Johnson.

Norton[1] has discussed subaqueous gliding as a cause of a certain type of breccias, but examples certainly coming under this category are apparently not common.

[1] W. H. Norton, *Jour. Geol.*, Vol. XXV (1917), pp. 182–85.

ACTION OF ICE

Intraformational contorted clays have, by various writers, been attributed to the action of ice but, as a rule, there has been little or no attempt to really analyze the structures involved. Salisbury and Atwood,[1] in their discussion of an extinct glacial lake near Devil's Lake, Wisconsin, figure and very briefly describe intraformational contorted clays. They say: "The grounding of an iceberg on the surface before the overlying layers were deposited, or the action of lake ice, may have been responsible for the singular phenomenon." In accordance with criteria set forth in the foregoing discussion of the Connecticut Valley clays, the writer believes that this corrugated zone must have resulted from differential movement after deposition of the overlying beds. The remarkable uniformity of thickness of the contorted zone; its relatively regular (nearly straight) upper surface; and the gently bent immediately overlying beds all strongly indicate that the corrugations developed under weight of the overlying beds. If the corrugations were caused by thrusting action of ice upon surface layers would not the contorted zone show notable variations in thickness and irregularity of its upper surface, and would not the overlying beds fail to show appreciable evidence of having been deformed? It is, however, conceivable that the corrugated zone may have resulted from differential movement brought about by the crowding action of ice against the upper portion of the whole body of clay, thus setting up a differential motion within its mass. Either this, or differential movement brought about under the action of gravity (in case the clays are at least moderately tilted), appears to have produced the corrugations.

J. Geikie,[2] in his description of the early postglacial deposits of the basin of the Forth in Scotland, says:

> Here and there also the beds (sands and clays) are much crumpled and confused, great sheets of clay being rolled over and over, and involving the associated sands for considerable distances. . . . . These are exceedingly irregular, and are just of such a character as we should expect would result from the grounding of ice rafts.

[1] Salisbury and Atwood, *Jour. Geol.*, Vol. V (1897), p. 143.

[2] J. Geikie, *The Great Ice Age* (1894), pp. 271–72.

Such contorted zones were quite certainly produced before the overlying clays were deposited, as proved by the notable variation in thickness of the contorted zone, its very irregular upper surface, and the manner in which the perfectly undisturbed overlying clays were laid down on the irregular surface.

W. A. Johnston[1] has described and figured an interesting case of notably crumpled sand forming a zone of variable thickness under till near Fort Frances, Ontario. He says that the crumpling of the sand was due to the over-riding action of glacial ice.

DIFFERENTIAL WEIGHTING

Kindle,[2] in his discussion of deformation of unconsolidated beds on the Avon River, Nova Scotia, describes "a section of finely laminated horizontal silts, which, for a thickness of one foot or more near the middle, have been distorted into a highly convoluted zone." He advances the hypothesis of differential weighting to account for the phenomenon and says:

> If a heavy load of sand were deposited over a portion of an area in which very soft beds were interpolated between more coherent strata, the more mobile would be likely to squeeze outward away from the sand pressure toward an unsupported edge, if one were developed by stream or wave cutting. This might occur without disturbing firmer beds above and below through the more yielding character of the soft beds.

According to Kindle, current scour would remove the heavier and coarser beds, after which horizontal layers would be deposited over the disturbed beds. He describes experiments in which clay beds in glass tanks were notably deformed by differential weighting with shot.

Some reasons for thinking that the foregoing explanation is not applicable to the Avon River occurrence, and quite certainly not to intraformational contorted clays in general as typified by the Connecticut Valley occurrences above described, are as follows: (1) Quite generally, in nature, there is no evidence of anything like notable current scour, but rather there has been continual deposition of the clays; (2) in the experiments the surfaces of the deformed

[1] W. A. Johnston, *Can. Geol. Surv., Mem. 82* (1915), p. 43 and Pl. 8.

[2] E. M. Kindle, *Geol. Soc. Amer. Bull.*, Vol. XXVIII (1917), pp. 323–32.

zones are very irregular, while in nature they are usually very regular, or even straight, for long distances; (3) such regular surfaces could hardly have resulted from vigorous current scour because the contorted zones are usually remarkably uniform in thickness for long distances; (4) there is almost invariably no evidence for the present or former existence of materials of such arrangement and character directly over the contorted zones as to give rise to very appreciable differential weighting; and (5) the contorted beds are seldom very much softer or more mobile than the inclosing strata.

CRYSTALLIZATION AND HYDRATION

In certain types of rocks, like gypsum and salt, there is strong evidence for the development of intraformational deformative effects by crystallization (or hydration) after their deposition. In the Zechstein salt of Germany,

> where the enclosing rocks are undisturbed, the layers of brightly colored bittern salts and of gypsum often show a remarkable flexuous, sinuous, or disrupted character. . . . . In the Salina deposit of central New York, some of the alternating salt and gypsum layers occasionally show a pronounced flexing and overfolding, while others are wholly undisturbed.[1]

In his discussion of the salt beds of western central New York, Luther[2] has reproduced an interesting picture of a small sharply overturned fold of rock salt between practically undisturbed beds.

The above-described examples occur in regions of non-folded and non-faulted strata, and it seems quite certain that "the main force was the endogenetic one due to the crystallizing force of the salts and to metasomatic process" (Grabau after Arrhenius).

Very fine examples of corrugations and crenulations occur within the gypsum deposits at Hillsborough, New Brunswick. According to Ami[3] "the gypsiferous deposits present evenly banded structure, between which there occur neatly folded layers in the form of ribbon-like corrugations" (Fig. 22). Kramm[4] states that "the gypsum rests upon a bottom of anhydrite and reaches a maximum thickness of perhaps 125 feet," and that gypsum was derived by

[1] A. W. Grabau, *Principles of Stratigraphy* (1913), p. 757.

[2] D. D. Luther, *N.Y. State Mus. Rept. 50*, Part 2 (1896), Pl. 4.

[3] H. M. Ami, *Geol. Soc. Amer. Bull.*, Vol. XXV (1914), p. 37.

[4] H. E. Kramm, *Can. Geol. Surv., Guide Book No. 1*, Part 2 (1913), p. 364.

hydration of anhydrite, as can be observed in many places. Since the gypsum beds occur in a very shallow syncline, the highly crenulated intercalated layers cannot have been caused by regional folding. The cause was, no doubt, the force exerted within the whole mass as a result of the great expansion during the transformation of anhydrite to gypsum. Differential stresses and strains set up locally in the whole mass caused localization of the corrugations (Fig. 9).



FIG. 9.—A specimen of gypsum from Hillsborough, New Brunswick, showing highly folded layers between less folded layers.

PRESSURE OF INTRUDING MAGMAS

Among the pre-Cambrian rocks of the Adirondack Mountains, New York, the writer has observed excellent examples of intraformational corrugations which are believed to have been direct effects of the pressure of magmatic intrusions. He has presented evidence[1] to support the view that the very ancient Grenville stratified series has never been subjected to severe regional folding throughout most or all of the Adirondacks. During the intrusion of the tremendous volumes of syenite-granite magma, the Grenville series was, however, badly cut to pieces so that many masses, both small and great, were tilted about in the rising magma and in many places subjected to notable differential pressure. The limestones, especially where they are near contacts with the syenite-

[1] W. J. Miller, *Jour. Geol.*, Vol. XXIV (1916), pp. 595–96.

granite, much more commonly exhibit local corrugations or crumplings than the other more rigid strata. Where a mass of the Grenville strata contains zones of well-bedded limestone intercalated between more rigid strata, and the whole has been subjected to differential pressure by the invading magma, the limestone layers have not uncommonly become contorted by differential movement within the mass while the adjacent beds above and below have been deformed little or not at all. In Figure 10, which well illustrates such a phenomenon in northern New York, the contorted beds of

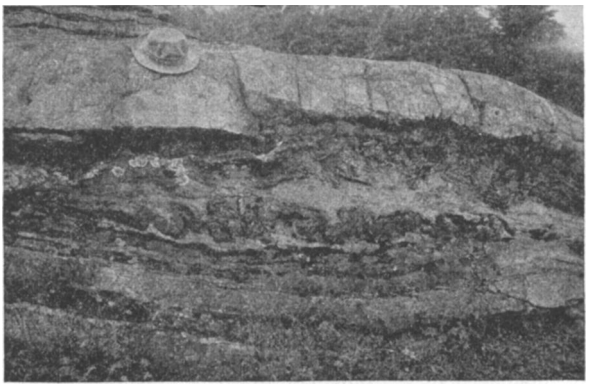


FIG. 10.—Crumpled beds of impure, thin-bedded, crystalline limestone between beds of only slightly disturbed garnetiferous gneiss north of Hermon, St. Lawrence County, New York.

very plastic impure limestone lie between heavy beds of rigid garnetiferous gneiss. This contorted limestone and its associated gneiss form part of a long narrow body of Grenville strata which was included in, and subjected to differential pressure by, a large body of granite magma, causing the more plastic limestone beds to crumple.

Spurr,[1] in his discussion of the Silver Peak region of Nevada, publishes a fine picture of intraformational contorted strata which occur on Mineral Ridge. In this region large volumes of granite magma invaded and cut to pieces Paleozoic strata made up of

[1] J. E. Spurr, *U.S. Geol. Surv. Prof. Paper 55* (1906), p. 108 and Pl. 21.

a comparatively thick series of thin-bedded, shaly, and calcareous sediments intercalated with beds of pure limestone, now metamorphosed into marble. The thin-bedded sediments are sometimes carbonaceous, sometimes streaked with sandy material. . . . . The limestone-slates are contorted on a minor scale. Most of this crumpling was probably due to the intrusion.

Beyond the last sentence quoted, Spurr says nothing regarding the cause of the intraformational crumpling. The available data rather clearly indicate that these corrugations, like those above described as occurring in northern New York, have been caused by the magmatic intrusion where a block of strata was more or less completely surrounded by the magma and subjected to differential movement, causing the more yielding layers to crumple.

Between 5 and 6 miles north of Northampton, Massachusetts, the writer has observed excellent examples of local contortions within the Leyden argillite (Paleozoic) formation near its contact with a basic phase of the Williamsburg granite. For about 2 miles parallel to the contact, irregularly distributed contortions are highly developed in the argillite for 10 to 20 rods out from the contact. Beyond that they rapidly diminish to disappearance. From the field evidence it seems clear that the corrugations resulted from differential movements within the argillite, caused by the shouldering pressure of the rising magma.

ACTION OF MAGMATIC INJECTION

In certain regions magmatic injection schists and gneisses contain local portions which are highly contorted. Many observations of such phenomena have been made by the writer in his study of the Adirondack Precambrian rocks. The following brief description of a certain district may best serve to illustrate the main principles involved. Extending 2 miles northeastward from just north of the village of Russell, St. Lawrence County, New York, there is a wide belt of mixed rocks containing fine exposures of amphibolite and garnetiferous gneisses intimately cut and injected, mostly parallel to the foliation, by moderately coarse-grained granite and pegmatitic granite, the whole mass being conspicuously banded. Just north of the village most of the mixed rock is notably contorted, while one-fourth to one-half of a mile farther east most of the rock is relatively straight-banded, but contains local highly contorted

zones. Still farther east the mixed rocks are nearly all straight-banded. It is believed that, during the forcing in of the magma, the whole mass of rock was notably plastic, and that local differential movements within the mass, caused by unequal pressures of the rising magma, resulted in the local corrugations.

MAGMATIC FLOWAGE

Finally, in our discussion of intraformational contorted rocks, differential magmatic flowage should be mentioned as a cause. Within certain areas of plutonic igneous rocks which exhibit primary foliation, there are not uncommonly local zones or bands in which the gneissoid structure, accentuated by dark minerals, appears to be irregular, wavy, or even contorted. The writer's experience in the Adirondacks shows[1] such local, contorted, primary flow-structures to be very common there, especially in the great syenite-granite series, and it is believed that they are essentially the result of varying magmatic currents under differential pressure, principally during a late stage of magma consolidation.

Lawson[2] has noted similar structures within certain granites of the Rainy Lake region of Ontario. He says: "The lines of streaking are very often not straight, but are wavy or contorted, sometimes intricately so, and are evidently due to slow movements in the magma prior to final consolidation."

[1] W. J. Miller, *Jour. Geol.*, Vol. XXIV (1916), pp. 611–12.

[2] A. C. Lawson, *Can. Geol. Surv., Mem.* 40 (1913), p. 93.